APPLICATION AND INSTALLATION GUIDE

GASEOUS FUEL SYSTEMS

G3600
G3500
G3400
G3300

CATERPILLAR®

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Foreword

This section of the Application and Installation Guide generally describes Gaseous Fuel Systems for Caterpillar® engines listed on the cover of this section. Additional engine systems, components and dynamics are addressed in other sections of this Application and Installation Guide.

Engine-specific information and data are available from a variety of sources. Refer to the Introduction section of this guide for additional references.

Systems and components described in this guide may not be available or applicable for every engine.

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Gaseous Fuel Systems

The fuel system on a gas engine is a highly specialized set of components that must deliver the correct amount of fuel to the cylinder at the precise moment it is needed. A well-designed fuel system enables the engine to produce maximum power at peak efficiency with a minimum amount of exhaust emissions.

This section discusses the components that make up a typical gas engine fuel system and how they work together to accomplish the mission stated above. It further discusses variations on these basic fuel systems that allow gas engines to deliver optimized performance while operating under challenging conditions, outlining the advantages, disadvantages and special considerations that accompany each system.

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Gas Engine Fuel System Components

The typical gas engine fuel system is comprised of several main components that serve a role in providing reliable fuel-air mixing in response to the engine's performance needs.

The recommended fuel train consists of three primary components (fuel filter, pressure regulator(s), and shut-off valve) in addition to the supply piping that is used to transport gas from the fuel source to the engine inlet. The recommended configuration to be used for Caterpillar gas engines can be seen in figure 1.

The customer is responsible for providing a fuel train that delivers fuel to the engine that meets the guidelines for the specific engine and application. Proper configuration of the fuel train including the selection of all components prior to the engine including but not limited to the supply piping, pressure regulators, fuel filter and gas shutoff valve will provide the required fuel pressure to the engine inlet while keeping pressure fluctuations within the limits for the engine (see price list).

Supply Piping

Although the supply piping is not part of the engine's fuel handling system, it is a primary component of the overall system; it supplies the gaseous fuel to the engine gas inlet connection. This supply piping must be designed to deliver the fuel flow rate required by the engine with a minimum of restriction. A fuel supply system with inadequate pipe diameter and/or too many bends in the piping can pose a restriction to flow that will come into play at higher load operating conditions, when the fuel demand is greatest.

If a fuel system is restrictive under steady-state conditions, the engine will be unable to achieve its full power potential because the fuel system cannot deliver the necessary amount of fuel to the cylinders. Even piping that is capable of adequate fuel flow at full rated power may experience restrictions under transient conditions. When an engine experiences a sharp increase in load, the change requires a corresponding increase in fuel flow. A poorly designed fuel supply system can resist this demand for increased fuel flow, causing the engine to struggle to take on the increased load.

The gas supply system can facilitate engine servicing by including strategically placed blocking valves. Blocking valves are used to manually shut off gas flow to parts of the system while components are being serviced or replaced. In some situations, blocking valves may be required by industry convention or code.

The following are important rules of thumb for the design of a proper gas supply system, however you should consult applicable industry guidelines and standards for any limitations that apply for each specific project:

- Pressure relief valves should be placed along the piping

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downstream of the regulator when allowed. Proper venting/ ducting for gases passing through the relief valve will need to be installed.

- Careful attention should be paid to connection types for components. Use adapters where necessary.
- Always design with supply piping at least as large in diameter as the engine gas inlet connection. Using a larger pipe diameter allows a greater margin of safety against the supply system being restrictive.
- Minimize bends and diameter changes in the fuel flow path near the engine, especially downstream of the engine's gas pressure regulator. All changes in direction (bend, elbows, etc.) and changes in diameter (expansions and/or reductions) represent a restriction to gas flow that must be taken in to account.
- Account for pipe diameter, valves, elbows, and other irregularities in the supply piping by computing an estimate of the system restriction in advance of engine installation. You should be able to verify through such calculations that the supply pressure and flow requirements of the engine will be available at the engine's gas supply inlet or you should redesign the supply system.
- Make certain gas supply piping is clean and free from debris and liquids.

Flexible Connection

The connection between the installation gas supply piping and the engine gas inlet is an important junction. Because the engine is subject to vibration during operation, the gas inlet connection can move relative to the fixed piping of the installation. Using a rigid joint at this connection forces the vibration to be taken up in the supply piping itself, leaving open the possibility of metal fatigue and failure resulting in a dangerous leak of flammable gas. This is easily addressed by using a flexible connection between the engine and supply piping.

Flexible connections for gaseous fuels must be suited to this service. They should be compatible with hydrocarbon gases and any other constituents found in the local fuel supply, including corrosive gases such as hydrogen sulfide, if present. They should also be suited to high temperatures that are possible to a limited degree during normal operation of the engine, but also in the event of a fire. Most flexible connections used for gas service use a stainless steel, single braided, annular corrugated flexible metal hose.

Shut-Off Valve

The gas shut-off valve (GSOV) is one of the most important safety device in the fuel system. Its role is to allow gas to the engine only when the engine is ready to use the gas. If the engine is not operating, or if the

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engine control has indicated it should shut down, the GSOV positively blocks the gas supply line to stop gas flow.

The GSOV can be as simple a device as a manually operated ball valve. However, most modern engines include automated safety systems that require direct control of the GSOV, so electrically driven solenoid-actuated valves are used for this purpose. Electrical power to operate these valves may come from on-engine sources ("self-powered" valves) or from an external power supply such as a set of batteries.

Caterpillar requires that the GSOV be defaulted to the shut down condition, requiring actuation to allow gas flow (an "energize-to-run", or ETR system). Different safety system design requirements may require that the GSOV be actuated to shut off flow (an "energize-to-stop", or ETS system), however this method is not recommended or supported by Caterpillar. If external powered is not available at the site, the self-powered GSOV must be used.

During normal operation of the engine, using the start-stop switch, GSOVs open and close as signaled by the engine control. Under these (normal stop) conditions, the ignition system is left active to fire the spark plugs while the engine runs down. This helps to burn fuel in the fuel lines between the GSOV and combustion cylinder, preventing fuel from being pumped into the exhaust system.

In an emergency shut down, the GSOV is closed and the ignition system is grounded immediately. This is done to stop rotation of the engine as quickly as possible, but it can leave unburned fuel in the engine and exhaust system. This unburned gas poses a hazard at restart in that it can be ignited by hot exhaust gases leaving the engine, resulting in an exhaust stack explosion.

CAUTION: Always purge the exhaust system after an emergency shut down to avoid potential exhaust system explosions due to unburned fuel in the exhaust stack. Purging the fuel from the exhaust system can be accomplished by cranking the engine while keeping the gas shut off valve closed and ignition system inactive.

GSOV type and size can be found in the engine price list. The typical mounting location of the GSOV is upstream of the gas pressure regulator, close to the engine. If the GSOV supplied by Caterpillar is not used, the customer supplied GSOV must be able to perform in a similar manner, acting to shut off the fuel immediately after the signal is given.

Filter/Coalescer

Gas engines, like most engines, require a fuel supply free from dirt and other foreign matter (including water). Foreign materials are understandably common to gas flows coming directly from the well, but even pipeline gas can pick up dirt, metal shavings, or weld slag left behind from pipeline construction, or scale and rust that develop in the pipeline during use.

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Left in the gas stream, particles and liquids can adversely affect engine performance or damage engine internal components, leading to reduced service life. Undesirable solids and liquids are removed from the gas stream using filters and coalescers.

Gas filters supplied by Caterpillar are designed to remove 99% of all the particles larger than 1 micron in diameter. Filters capable of removing even smaller particles may be required for sites with a high content of sub-micron debris. It is the customer's responsibility to provide clean, dry fuel to the engine. Expenses for damage caused by debris and abrasives in the fuel system are not warrantable.

Gas filters are not designed to handle liquids. Liquids in the fuel supply must be removed using equipment designed for that purpose. Bulk removal of liquids, such as de-watering at the well, is done with a scrubber. A scrubber is a large tank that slows the gas down, allowing miniscule droplets to fall out of the gas flow more easily. Mesh screens in the gas flow give smaller droplets a surface on which to collect, improving removal efficiency. The bottom of the tank serves as a collection basin for any liquids that fall out. Removal of very fine liquids from the gas stream is accomplished using a coalescer. A coalescer accomplishes this separation by causing smaller droplets of liquid to form larger droplets, which then gather on the surface of a filter and run off as collected liquid. Gas systems that include scrubbers and coalescers must have provisions for draining and disposing of the collected liquids.

Gas filters restrict the flow of gas in the supply line and must be included in supply restriction calculations. To ensure proper pressure at the gas pressure regulator, the fuel pressure supplied to the fuel filter must be equal to the requirement at the pressure regulator plus the maximum restriction of the fuel filter and pipe restriction between the pressure regulator and fuel filter. Monitoring filter restriction during use is made possible by placing pressure taps or gauges both upstream and downstream of the filter. The pressure drop measured in this manner can serve as an indication of the condition of the filter and whether or not it is time to change the filter element.

Figure 1 shows a typical fuel filter installation schematic for a Caterpillar gas engine. Consult the price list for fuel filters for specific engine models. When using fuel filters not provided by Caterpillar, always size the filter based on the minimum fuel line pressure and highest expected flow. Fuel flow for each engine model can be determined from the technical data sheet for the specific engine and rating and should be adjusted for fuel consumption tolerance and changes in the energy content of the fuel.

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Fuel Train Configuration

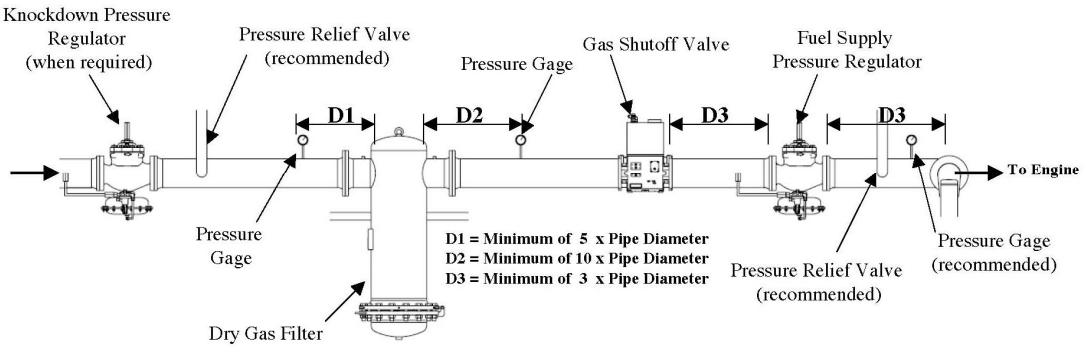

Figure 1

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Example:

Determine the fuel flow of a G3516 LE 8:1 C/R engine rated at 943 BkW (1265 bhp) at 1400 rpm, 54°C (130°F) Separate Circuit Aftercooling (SCAC) when operating on 33.4 MJ/Nm^3 (850 btu/ft^3) LHV fuel.

Fuel flow from TMI data:

291.5 Nm^3/hr @ 35.57MJ/Nm^3 LHV fuel

(10,863 ft^3/hr @ 905 Btu/ft^3 LHV fuel)

Determine Energy Flow Rate:

Energy Flow Rate =

291.5 Nm^3/hr x 35.57MJ/Nm^3 = 10,369 MJ/hr

(10,863 ft^3/hr x 905 Btu/ft^3 = 9,831,015 Btu/hr)

Determine Fuel Flow at 33.4 MJ/Nm^3 (850 Btu/ft^3):

Fuel Flow at 33.4 MJ/Nm^3 =

10,369 MJ/hr / 33.4 MJ/Nm^3 = 310.4 Nm^3/hr

Fuel Flow at 850 Btu/ft^3 =

9,831,015 btu/hr / 850 btu/ft^3 = 11,566ft^3/hr

Determine Fuel Flow for Sizing Filter with 5% Tolerance on Fuel Flow:

Fuel Flow for Filter Sizing =

310.4 Nm^3/hr x 1.05 = 325.9 Nm^3

(11,566 ft^3/hr x 1.05 = 12,144 ft^3/hr)

Gas filters should be installed according to the manufacturer's recommendations and installation guidelines. Some rules of thumb for a successful filter installation include:

- Note the flow direction indicated on the filter cap when installing the filter. Incorrect installation will cause a higher pressure drop across the filter and result in improper operation.
- Mount the filter vertically and as close to the engine as possible.
- Position the filter so there is adequate room for servicing.
- The upstream pressure tap should be a minimum of 5 pipe diameters from the filter inlet and the downstream tap should be a minimum of 10 pipe diameters from the filter outlet.
- Pipe unions can be installed to simplify removal of the filter housing, but they should not be located between the pressure measuring points.
- Install a valve to vent the filter for maintenance. This valve should be connected to a pipe to route the vented gas away from the engine and any other possible ignition sources. All venting installation should meet codes for disposal of flammable gas.

Pressure Regulators

The gas pressure regulators controls the supply of fuel to the on-engine fuel system. This is a critical role in support of the fuel system because the fuel metering done by the fuel system often depends directly on the pressure of the fuel supply. To fulfill its role in the system, the gas pressure regulators must:

- Step gas pressure down to a value appropriate for the fuel mixing equipment, and

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- Dampen out any fluctuations in the supply pressure to stabilize the supply to the mixer.

As with gas filters and other components in the gas stream, the proper regulator for a given application depends on the specific installation, including details such as gas specific gravity, temperature, pressure, flow rate, and desired outlet pressure. All applications require at least an engine pressure regulator, which is used to maintain the appropriate pressure to the engine fuel inlet. In addition certain applications will require a second pressure regulator also known as a knockdown regulator prior to the fuel filter to decrease the pressure from the fuel supply to a level that is less than or equal to the maximum outlet pressure of the engine pressure regulator. If the external supply pressure is too high to accomplish the desired pressure reduction in a single step (high pressure gas on a low pressure package), or if the pressure fluctuations in the external supply are too large, a knockdown pressure regulator may be required prior to the fuel filter to deliver the desired gas pressure to the engine pressure regulator. As was stated for gas filters, gas pressure regulators should be installed according to the manufacturer's recommendations and installation guidelines. Some rules of thumb for a successful gas pressure regulator installation include:

- To prevent pressure buildup ("dead head" condition) avoid providing gas inlet pressures above the maximum downstream pressure rating for a regulator.
- Install the regulator in the correct gas flow direction and downstream of the fuel filter.
- Piping to the gas regulator must be at least as large as the regulator inlet/outlet ports.
- The regulator should be positioned so there is a length equivalent to three pipe diameters of straight pipe upstream and downstream from the regulator.
- The pressure regulator must be adjusted at the engine installation site.

As noted above, the gas pressure regulator works closely with the fuel-air mixer to make the fuel system function properly. The gas pressure regulator set-up should be matched to the needs of the fuel-air mixer and engine requirements. The recommended configuration to be used for Caterpillar gas engines can be seen in figure 1. Additionally Caterpillar recommends that each package has its own dedicated engine pressure regulator. An engine pressure regulator should not be used for multiple engines.

Gas pressure regulators are configured to deliver various pressures for various engines. **Table 1** shows the various gas pressure requirements for the G3300, G3400, G3500 and G3600 engines.

Fuel-Air Mixer

The fuel-air mixer is the heart of a gas engine fuel system. The mixer meters the proper fuel flow rate to

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match engine operating conditions to simultaneously meet the demands of engine power, load acceptance, and exhaust emissions while accounting for the impact of ambient air temperature and pressure and gas quality.

Perhaps the most widely used device to accomplish this function is the carburetor, which uses the inlet airflow to gauge the proper amount of fuel to admit for current operating conditions. Systems that are more complex actively monitor the conditions of the incoming fuel and air streams to make possible other fuel-air mixing schemes; some of these schemes will be described later in this section.

Throttle

The throttle is not directly a part of the fuel system, but it has a direct influence on the fuel system so it is appropriate for this discussion.

The throttle is the device that regulates engine performance by controlling the flow of air (or fuel-air mixture) to the cylinders. It typically takes the form of a butterfly valve in the inlet air system and is mounted as close to the cylinders as the engine design will allow. Because the throttle regulates airflow, it is directly responsible for one of the most important inputs to the fuel system. The airflow rate combined with the desired air/fuel ratio determines the fuel flow rate that the fuel system must provide to meet the current engine operating conditions.

Gas Supply Pressure Requirements*		
Pressure	Minimum kPa (psig)	Maximum kPa (psig)
G3300		
Low Pressure Gas	10 (1.5)	69 (10)
High Pressure Gas	83 (12)	172 (25)
G3400		
Low Pressure Gas	10 (1.5)	35 (5)
High Pressure Gas	138 (20)	172 (25)
G3500		
Low Pressure Gas, Impco	10 (1.5)	35 (5)
Low Pressure Gas, Deltec	41 (6)	83 (12)
High Pressure Gas		
Low Emission 11:1 C/R	207 (30)	276 (40)
Low Emission 8:1 C/R	241 (35)	276 (40)
Standard TA	172 (25)	207 (30)
Naturally Aspirated	14 (2)	69 (10)
G3600	380 (55)	1034 (150)
* Supply pressure to the fuel regulator.		

Table 1

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Fuel Systems Equipment for Special Conditions

Gas engines are frequently placed in service where prevailing conditions place special demands on fuel system performance. For many of these situations, special equipment can be incorporated into the fuel system to adjust for special conditions.

Fuel Heater

Many fuel metering-mixing schemes rely on a volume-to-volume basis for properly matching fuel flow to airflow. Unfortunately, air and gas volumes are directly dependent upon temperature, making the temperature of the inlet gas an important parameter for proper fuel system operation. Also, hydrocarbon fuel gas streams are typically made up of a mixture of many different hydrocarbon gas fractions, each with their own qualities. Many of the heavier fractions tend to exist as liquids at lower temperatures, making control of fuel stream temperature an important tool in preventing the unwanted dropout of hydrocarbon liquids in the fuel delivery system.

To resolve these issues, it is possible to install a heat exchanger in the fuel delivery system to serve as a fuel heater. The most convenient source for heat for such a device is the jacket water system on the engine. Because fuel heaters are required only under extreme circumstances, they should be mounted as close to the engine as possible to minimize any change in temperature after the gas leaves the heater. Similarly, the fuel lines between the fuel heater and the engine should be insulated to minimize heat loss. The heater should be located upstream of the gas pressure regulator to avoid any impact on gas supply pressure.

Ferrous Fuel System

There are many applications for gas engines where the installation environment is considered hazardous due to the possible presence of an explosive gas-air mixture. Because fire is a threat, special rules are applied that tailor the devices and materials used in that area to minimize their contribution to the fire hazard. The fuel system is one of the areas on the engine that can get special attention under these conditions.

For hazardous environments, some engine models have an available option for a “ferrous” fuel system, in which certain components of the standard fuel system are replaced with similar parts made from ferrous materials (iron or steel). The ferrous materials can withstand higher temperatures than other common materials such as aluminum.

Corrosive Fuel System

Materials hazardous to fuel system components are not all from external sources. Certain gas streams can carry a significant amount of corrosive compounds that can damage the fuel system. For these situations, certain gas engine models offer a corrosive fuel system option

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as part of an overall engine operation strategy to accommodate the potentially damaging effects of corrosive compounds in the fuel gas.

A corrosive fuel system is modified in a manner that replaces any components susceptible to corrosive attack with similar parts made of less vulnerable materials. Materials to be removed include the so-called “bright” metals, like aluminum and copper. Of course, given that the fuel and air are mixed prior to entering the cylinders on many engine configurations, any other components on the engine that are exposed to the gas must also be modified or replaced with more robust substitutes. Components such as the aftercooler (on engines with pre-turbocharger fuel-air mixing) must be tailored to the corrosive presence in the fuel gas. Corrosive components remaining in the gas after combustion must also be addressed. Elevated jacket water temperatures may be used to help keep the corrosive compounds from condensing out of the blowby gases in the crankcase. The allowable limits for corrosive compounds in the fuel are described in the Gaseous Fuels section of the Application & Installation Guide.

Fuel Accumulator

Some situations such as landfill or biogas applications may provide additional challenges with varying gas pressures and/or energy content being supplied to the fuel train. In these instances and accumulator tank may need to be installed to help provide a buffer to minimize these variations that the fuel train and engine may see and to keep the fluctuations within the limits of the engine.

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Carbureted Fuel Systems

The heart of the carbureted fuel system is the carburetor. The carburetor is designed to mechanically monitor airflow and mix in the proper proportion of fuel to achieve the air/fuel ratio desired for a specific engine operating condition. This is accomplished by the use of a venturi, a narrowing in the airflow path that creates a pressure drop in the flow. Because the properties of this pressure drop are predictable, it can be used to create controlled conditions for accurately metering a gas flow to create a fuel-air mixture flow with a desired air/fuel ratio. As noted earlier, the carburetor relies on the gas pressure regulator to deliver a stable, predictable gas flow to make this process work. Also included in the system is a load adjustment valve that allows for fine-tuning the system's mixing properties to match the prevailing conditions at each installation. A general schematic of a carbureted fuel system is shown in **Figure 2**.

Standard Natural Gas System
(Turbocharged-Aftercooled or Naturally Aspirated)

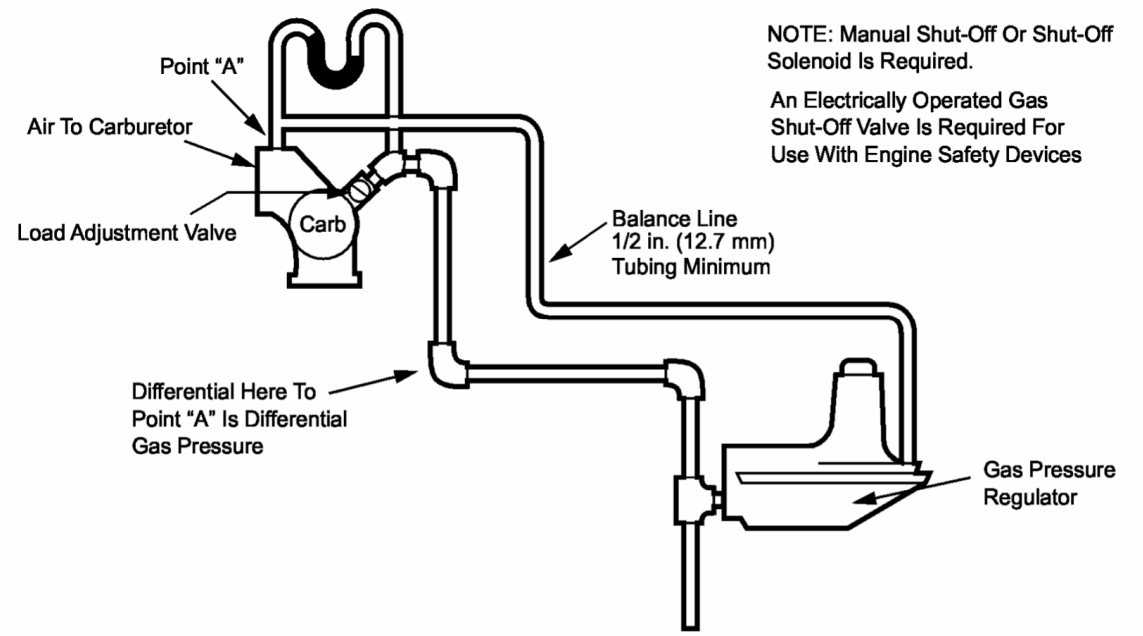
NOTE: Manual Shut-Off Or Shut-Off Solenoid Is Required.
An Electrically Operated Gas Shut-Off Valve Is Required For Use With Engine Safety Devices
Point "A"
Air To Carburetor
Load Adjustment Valve
Carb
Balance Line 1/2 in. (12.7 mm) Tubing Minimum
Differential Here To Point "A" Is Differential Gas Pressure
Gas Pressure Regulator

Figure 2

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Gas Differential Pressure Regulator

In a carbureted fuel system, the gas pressure regulator is set up to function as a differential pressure regulator. A differential pressure regulator doesn't necessarily maintain a constant gas pressure. Its goal is to maintain a constant gas pressure differential relative to the static pressure of the airflow at the inlet to the carburetor-mixer. As air pressure to the carburetor increases, fuel pressure is maintained equal to air pressure plus the gas differential pressure. The gas differential pressure is typically set to 1.0 to 1.3 kPa (4 to 5 inches of water) by adjustment of the spring acting on the diaphragm inside the regulator. This constant differential pressure allows the carburetor to adjust its air/fuel ratio mixing to accommodate a wide range of engine operating points based on their air demand.

A typical gas differential pressure regulator is shown in **Figure 3**.

Typical Gas Differential Pressure Regulator

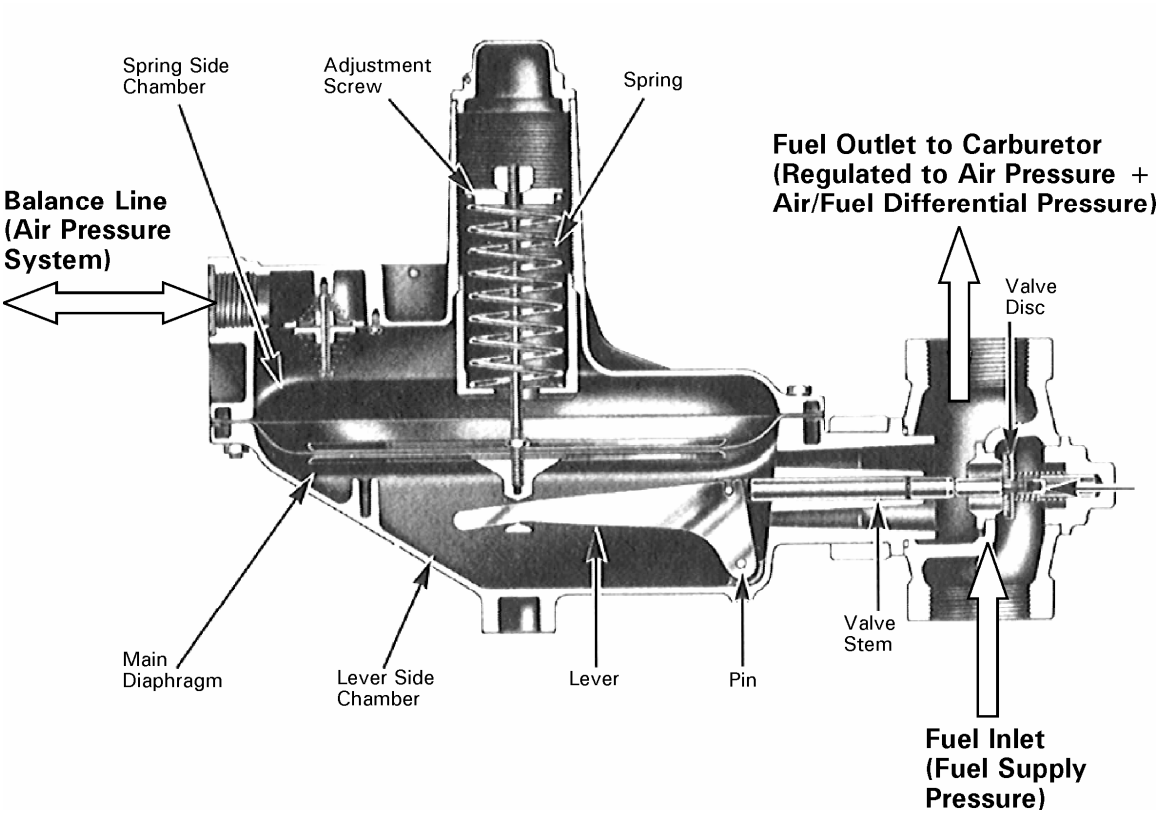

Figure 3

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When the forces on both sides of the diaphragm are the same, the regulator sends gas to the carburetor at a constant rate. The balance line between the regulator and carburetor must be in place to maintain the proper force balance. A turbocharged engine will not develop full power with the balance line disconnected. With proper adjustment of the spring, gas pressure to the carburetor will always be greater than carburetor inlet air pressure, regardless of load conditions or turbocharger boost pressure. Gas differential pressure regulators have flow capacities based on supply pressure to the regulator, body size and internal orifice size. Gas supply pressure requirements for each engine family are shown in **Table 1** earlier in this section.

Load Adjustment Valve

The load adjustment valve is a variable orifice in the fuel line between the carburetor-mixer and the differential pressure regulator as shown in **Figure 4**. Its purpose is to provide a means to fine-tune the air/fuel ratio setting of the fuel system for site ambient conditions and fuel quality. It does this by throttling the gas flow delivered by the gas differential pressure regulator; lowering the gas pressure relative to the airflow in the carburetor will produce a leaner mixture and vice versa. The valve can only effect changes within a certain range of adjustment. However, the specific range covered by a given fuel system set-up can be altered by changing the carburetor internal components to shift the fuel-air mixing characteristics. These larger changes in air/fuel ratio are accomplished by changing the gas valve-and-jet combination in the Impco carburetor or the venturi in the Deltec carburetor. Such large-scale changes in the carburetor are typically tied to the lower heating value of the fuel gas. The load adjustment valve is typically used to dial-in the selected fuel system for site conditions.

Carburetor-Mixer

The carburetor-mixer's main function is metering and mixing the fuel and air prior to entering the combustion chamber. Proper mixing depends on the carburetor being sized for the appropriate fuel and the fuel being supplied to the carburetor at the proper pressure. Caterpillar uses a Deltec or an Impco carburetor to properly mix and meter gas fuels.

Deltec Carburetor

Figure 4 shows the venturi-type (Deltec) carbureted fuel system used on Caterpillar gas engines. The venturi carburetors are manufactured by Deltec and are used on some low-pressure gas engines. Venturi carburetors operate on the venturi effect which, simply stated, says that as air flows through a venturi its pressure is lower in the venturi (**P2** in **Figure 4**) than it is upstream (**P1** in **Figure 4**). The higher the airflow, the greater the differential pressure will be. If, at the same time, the gas pressure to the carburetor (**P3** in **Figure 4**) is held constant with respect to **P1**, the pressure differential **P3**-**P2** will increase as airflow increases. Any

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increase or decrease in this differential pressure will cause a corresponding change in fuel flow. The gas pressure regulator is used to keep the pressure difference between **P3** and **P1** constant.

Engine power and emissions setting are determined by the mass air/fuel ratio entering the combustion chamber. A carbureted system, however, maintains a fixed volume ratio of air and fuel, and therefore does not maintain constant performance with changes to air temperature, fuel temperature or fuel composition. This is particularly important in applications where low exhaust emissions are a necessity since emissions will change with changes in mass air/fuel ratio. Depending on carburetor design, emissions can vary throughout the load range.

Note: Most engines come standard with natural gas carburetors which are designed for fuels with lower heating value ranges from 31.4 to 55.0 MJ/Nm^3 (800 to 1400 Btu/scf). The price list also defines the heating values ranges for optional carburetors. If the fuel to be used does not fall within the heating value ranges specified, consult the factory for assistance in carburetor sizing.

Cross Section of a Typical Deltec Carburetor-Mixer

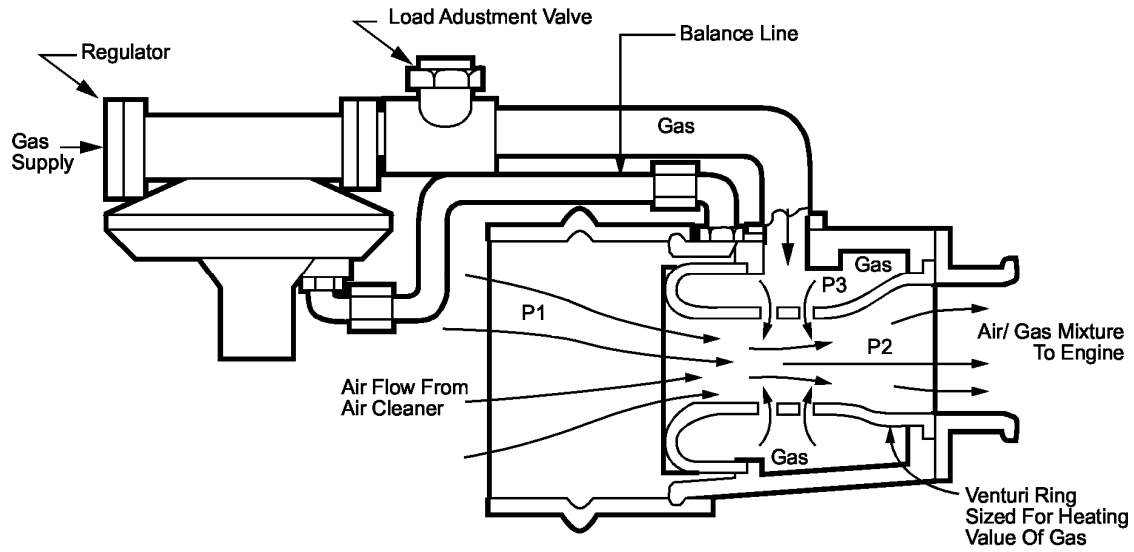

Figure 4

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Impco Carburetor

Figure 5 is a cross section of a typical Impco carburetor mixer. This system is used on all high-pressure carbureted gas applications and some low-pressure carbureted gas applications. As air flows past the carburetor diaphragm vacuum port, a vacuum is created. This vacuum is sensed by the air valve diaphragm, which in turn raises or lowers the gas valve as the airflow increases or decreases accordingly. This allows the carburetor to adjust the fuel flow in proportion to airflow. The gas valve and jet are sized for specific fuel and operating condition ranges. For example, a carburetor containing a gas valve and jet sized for natural gas would not operate properly on landfill gas. Likewise, operation with a three-way catalyst requires a different valve and jet than operation with no catalyst. It is very important that the engine is equipped with the proper valve and jet.

Note: Contact Caterpillar for proper application of these valves and jets.

The air/fuel ratio is adjusted by setting the regulator differential pressure and the load adjustment valve. Instructions for correctly adjusting the air/fuel ratio can be found in the service manuals.

Cross Section of Typical Impco Carburetor–Mixer (600 Series Varifuel Mixer – Cut-Away)

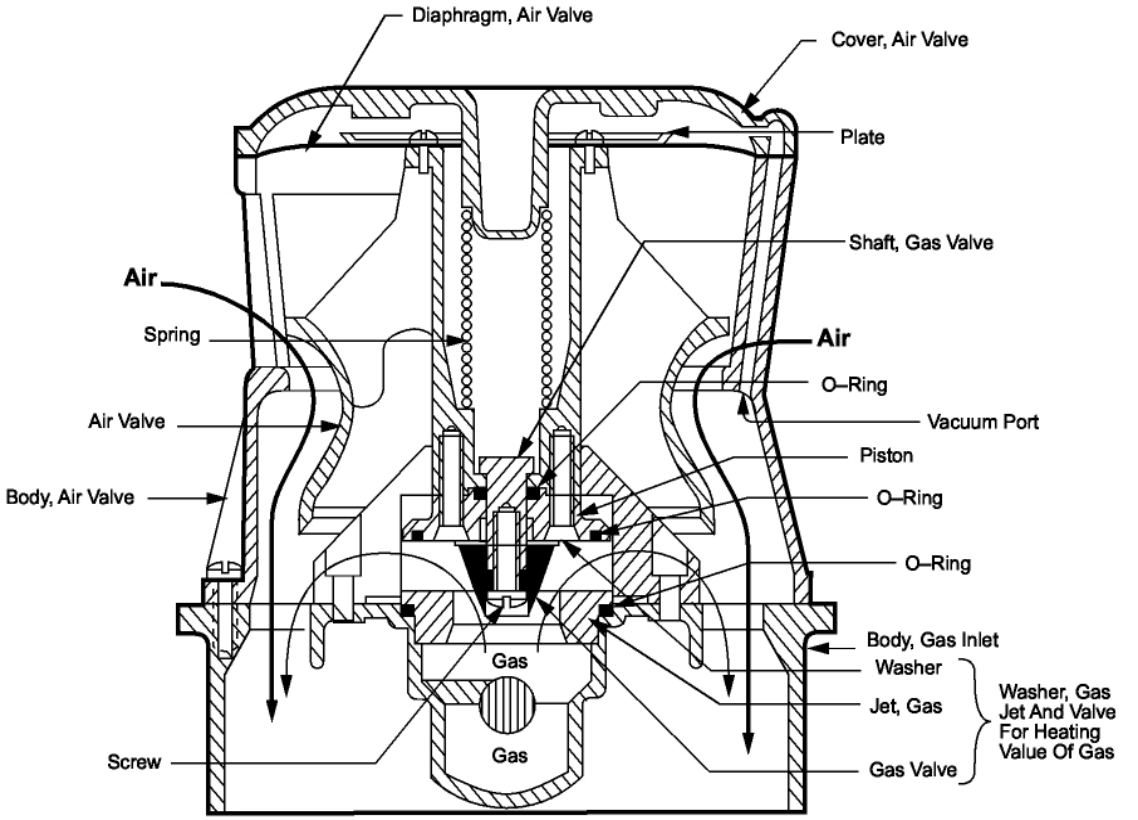

Figure 5

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High- and Low-Pressure Carbureted Fuel Systems

The components involved in a carbureted fuel system remain largely the same regardless of how the system is adapted to a given engine design. However, the nature of the design does dictate certain operating attributes of the fuel system. One of those attributes is the operating fuel pressure range. Simply due to the placement of the carburetor relative to the turbocharger in the air system, the carbureted fuel system can be configured as a high- or low-pressure system.

In a high-pressure fuel system, fuel-air mixing is done downstream of the turbocharger, after the inlet airflow is boosted. Refer to **Figure 6**. Because of this ordering of components (carburetor after turbocharger), the fuel system must be able to deliver the fuel gas to the carburetor at a higher pressure than that of the boosted air stream; anything lower and the fuel cannot be forced to flow into the air stream. High-pressure gas fuel systems operate on gas supply pressure ranging from 140 kPa (20 psig) to 280 kPa (40 psig) depending on the engine model.

High-Pressure Gas Carbureted Fuel System

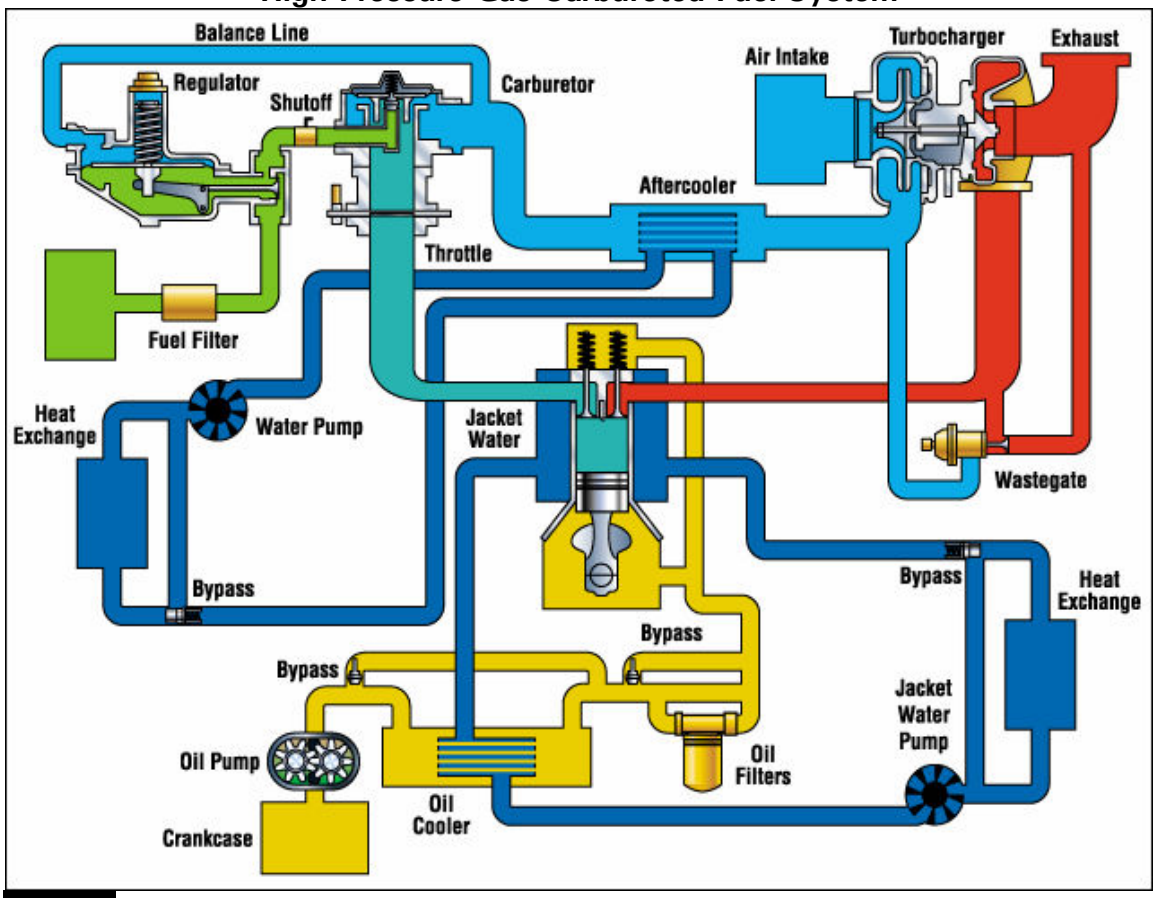

Figure 6

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In a low-pressure system, the ordering of components is reversed, with the carburetor located upstream of the turbocharger. Refer to **Figure 7**. In this order (carburetor before turbocharger), the carburetor does not have to manage the boosted air stream, so fuel supply pressure requirements are much lower. Low-pressure gas fuel systems operate on gas supply pressure ranging from 7 kPa (1 psig) to 70 kPa (10 psig) depending on the engine model. The low-pressure system is often used in situations where gas supply pressures at a particular site are limited, either by building code or by the gas supply source itself.

Low-Pressure Gas Carbureted Fuel System

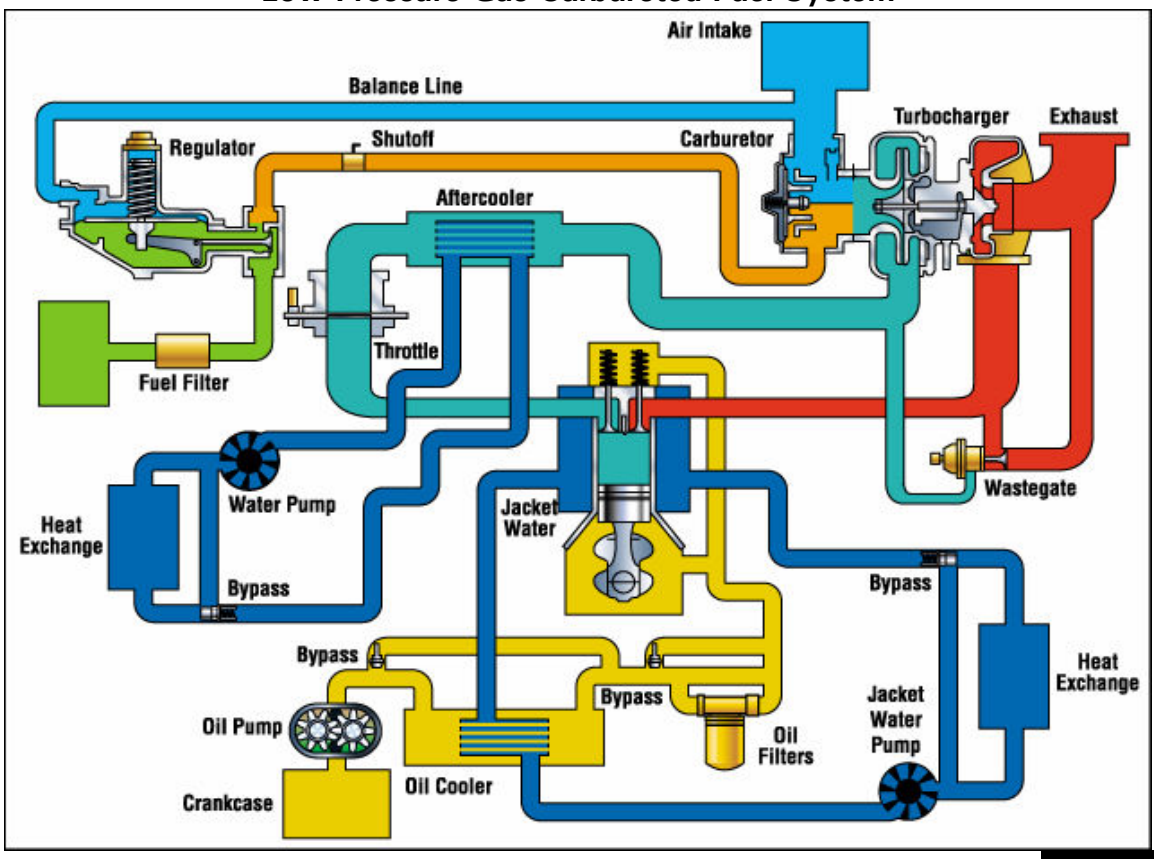

Figure 7

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Dual Gas Fuel Systems

It is possible to set up a gas engine to run on two very different gaseous fuels. Such an arrangement is known as a dual gas fuel system. Dual gas fuel systems are typically put into service for gas streams with very different heating values, such as landfill/digester gas and natural gas or natural gas and propane. Dual gas fuel systems allow an engine the flexibility to use fuel streams that may not always be available because the second fuel source serves as a backup for the first.

A simple dual gas setup uses two gas pressure regulators feeding into a single carburetor; this type of system is shown in **Figure 8**. The primary fuel in a two-regulator system is always the lower energy content gas of the two (see **Table 2**). This makes it possible to tune both fuel streams by adding a second load adjustment valve in the supply line from the backup regulator. In this way, the primary fuel stream is tuned at the adjustment valve on the carburetor inlet and the secondary fuel stream is tuned at the secondary adjustment valve.

The following guidelines are given for automatic switching between the primary and secondary fuels for the following combinations.

Primary Fuel	*Secondary Fuel*
Digester	Natural Gas
Natural Gas	Propane

Table 2

In each of these systems, the primary fuel is the low Btu fuel and the secondary fuel is the high Btu fuel.

Note: Dual regulator systems for digester-propane are not recommended. The engine will be difficult to start due to the negative pressure required to obtain the correct air fuel ratio on propane.

Dual regulator systems can transfer between the primary and secondary fuel while under load. It is recommended that the fuel regulators not be moved from the factory mounting. Any increase in fuel line length can cause problems with smooth transfer between the primary and secondary fuel. The solenoid operated shutoff valves should be energized to run, and be mounted as close to the fuel regulators as possible. During normal operation on the primary fuel, both solenoid valves should be engaged. The primary fuel gas, supplied by low Btu regulator, is always at a greater pressure than the secondary fuel supplied by high Btu regulator; therefore, when the primary fuel is present, the secondary regulator will shut off the secondary fuel, even though the solenoid valve is energized.

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Dual Fuel Turbocharged or Naturally Aspirated Engines

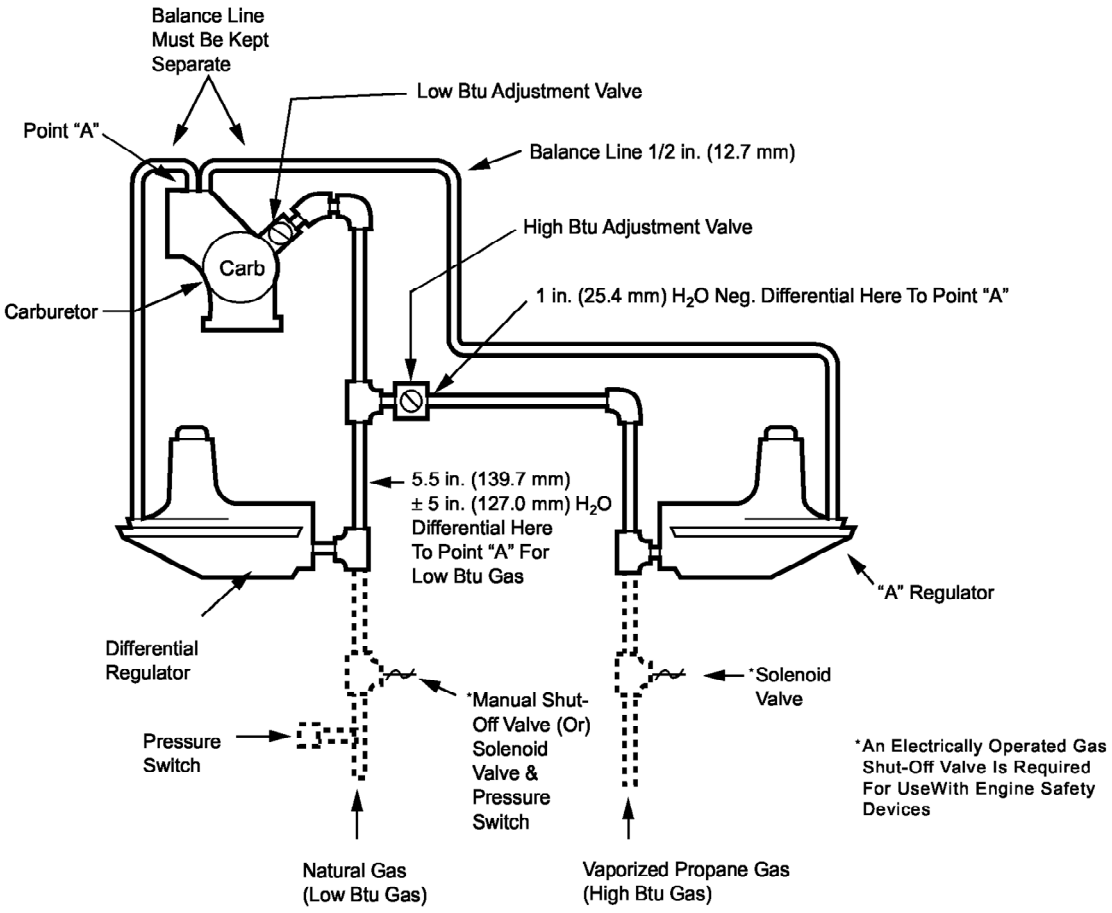

Figure 8

To transfer to the secondary fuel, de-energize the low Btu solenoid valve. As the primary fuel is used in the fuel line between the low Btu pressure regulator and the carburetor-mixer, the pressure in the line will drop. As this gas pressure becomes negative, the secondary regulator will sense the drop and open to supply secondary fuel to the carburetor. Circuits that attempt to switch from primary to secondary fuel by flip-flopping the solenoid valves are usually not successful and are not recommended.

Another approach to providing dual gas capability involves putting two complete fuel systems on the same engine. In this type of arrangement, each fuel system is tuned in the normal manner. The challenge with this arrangement is finding space to fit in two sets of fuel metering and mixing equipment. Dual fuel systems with regulators and mixers for each fuel can be automatically switched, but the engine must be at no load. These systems will require a flip-flop solenoid arrangement. If switching fuel supplies under load is a

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requirement, a programmable controller is required to control switching from one fuel to another.

The time delays for the solenoid values will need to be determined at the site for changeover. For automatic switching between primary and secondary fuel, a dual timing magneto or EIS is required. Place the activation switch for the dual timing between the primary fuel solenoid and the primary fuel regulator. As long as primary fuel pressure is supplied to the engine, the timing will be in the advanced position. Once the primary fuel pressure is lost, the ignition will index for operation on the secondary fuel.

Air/Fuel Ratio Control Systems (AFRC)

General Description

Air/fuel ratio controlled (AFRC) engines take mixing of fuel and air one step further than simple carbureted systems. While the carburetor is capable of adjusting the fuel mixing rate to match different airflow rates, it can only sense the volume flow rate of air and fuel. It cannot account for the effects of temperature on the density of air and gas; nor can it account for other factors, such as changes in humidity or in fuel heating value.

Simple Feedback AFRC (High- and Low-Pressure Carbureted Systems with Exhaust Oxygen Sensor)

Air/fuel ratio control offers the ability to maintain a specific level of NOx emissions even when there are changes in load, fuel heating value or ambient conditions. Real measuring and adjusting for all of the factors that affect combustion would require an incredibly complex and impractical control system.

Instead of measuring multiple parameters of the incoming fuel and air, AFRC systems monitor key output parameters that provide a direct measure of how closely combustion matches the desired condition. This approach is known as closed-loop feedback control. In AFRC systems, the most commonly used feedback parameter is the amount of oxygen in the exhaust stream because it tells how much oxygen was left after the fuel was burned. Because most, if not all, of the oxygen in the combustion chamber comes from the air in the inlet charge, exhaust oxygen levels are a direct result of the air/fuel ratio being provided.

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Simplified Example of an Air/Fuel Ratio Control

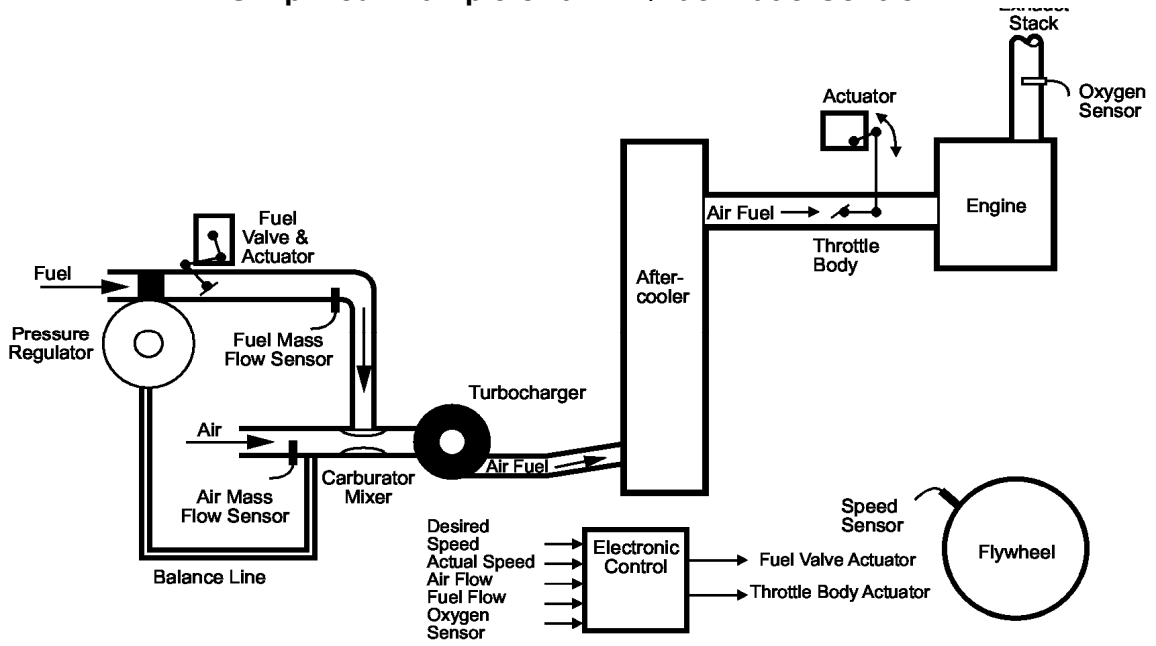

Figure 9

Figure 9 shows an AFRC system based on a carbureted engine. An oxygen sensor in the exhaust stack measures the oxygen level in the exhaust. This information is provided as feedback to the AFRC, which compares the measured oxygen level to that of the correct air/fuel ratio for the desired emissions setting. The AFRC then makes corrections to the fuel flow in the carburetor by adjusting an actuator-controlled butterfly valve in the fuel supply line. By manipulating the fuel pressure being supplied to the carburetor, the AFRC can dial in the air/fuel ratio that is correct for the engine setting under the prevailing operating conditions.

Caterpillar offers exhaust oxygen feedback systems for several lean-burn gas engine models. The version available for high-pressure gas fuel systems is designed for use with natural gas in the range of 33.41 to 50.12 MJ/Nm^3 (850 to 1275 Btu/SCF). A version is also available for low-pressure gas lean-burn engines operating on pipeline-quality natural gas or low-energy fuels such as digester gas or landfill gas. These systems deliver constant NOx emissions levels across the engine's defined continuous-duty load-speed range.

Note: The Caterpillar air/fuel ratio control system is compatible with the following:

- Customer Communication Module (CCM, gas engine version).
- Woodward load share interface module (PWM version).

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- Woodward digital synchronizer and load control (DSLC).
- Fisher suction pressure controllers (4-20 mA or 0-15 psi output).

For more information on the G3500 air/fuel ratio control system, consult the Systems Operation and Troubleshooting sections of the G3500 Service Manual.

AFRC is not only used for lean-burn engines. It is also necessary when using three-way catalytic converters. In order for a three-way catalyst to operate as designed, the NOx and CO emissions must be approximately equal, which in turn requires that the air/fuel ratio be kept at a specific setting. This emissions setting is achieved by operating the engine at a near-stoichiometric air/fuel ratio, with about 0.5% excess oxygen in the exhaust. An exhaust oxygen feedback AFRC is well equipped to monitor this exhaust oxygen level and make the adjustments to air/fuel ratio that allow the catalyst to provide optimum emissions reduction.

Caterpillar does not offer AFRC systems from the factory for use with stoichiometric engines operating with three-way catalysts; however, these control systems are widely available. Note that when using a three-way catalyst with the Impco fuel systems, the carburetor valve and jet must be changed to match the type of air/fuel ratio control device you have selected.

Combustion Sensing Feedback AFRC (G3600 Prechamber/Gas Admission Valve Fuel System)

AFRC systems aren't restricted to use with carbureted fuel systems, nor are they limited to using exhaust oxygen as the feedback signal. An example of a different approach is the combustion sensing AFRC integrated into the engine control strategy on the G3600 family of gas engines.

The G3600 fuel system starts with the same fuel supply components described earlier for the same reasons: to deliver a stable, predictable source for fuel gas. Beyond the gas pressure regulator, things begin to look very different. The G3600 uses a gas admission valve fuel mixing strategy in support of an enriched prechamber combustion system. Both are notably different from the carbureted systems discussed above and thus require some description.

Gas Admission Valve (GAV) Fuel System

The gas admission valve (GAV) is a much simpler device for fuel mixing than a carburetor, but as such, it relies on the supporting control system to deliver the proper air/fuel ratio to the engine. A GAV is simply a valve in the air inlet path that is opened or closed to allow fuel gas to flow into the inlet airflow. On the G3600, the GAV is cam-driven and is located in the air inlet elbow leading to each cylinder head. Because the G3600 is a turbocharged engine, the GAV fuel system requires a high-pressure fuel

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gas supply to allow the gas to flow into the boosted inlet air stream.

Metering the fuel mixed into the airflow requires precise measurement of the pressure and temperature of the air and gas flows, coupled to timing of the opening and closing of the valve. Given a fixed differential pressure of gas over air pressure, a specific amount of gas could be mixed with the air stream by controlling the time duration that the GAV is open. The G3600 system uses the opposite approach, opening the GAV for a fixed period of time and regulating the gas-over-air differential pressure to control fuel metering.

Enriched Prechamber Combustion System

As air/fuel ratio becomes leaner, the amount of energy required to establish stable combustion increases and, at some point, the ability of a simple spark plug to deliver sufficient energy becomes impractical. An enriched prechambered combustion system uses a separate chamber outside the main cylinder to start combustion. The prechamber, with its own small feed of fuel gas, provides a controlled environment with a richer air/fuel ratio that greatly improves combustion conditions, and makes it possible to operate the main chamber mixture at the very lean air/fuel ratio that enables the G3600 to produce very low NOx emissions.

G3600 Fuel System and AFRC

The G3600 fuel system is built around a fuel rail delivering gas to both the GAVs and the prechambers on each cylinder. Fuel flow through the GAVs is timed by the camshaft actuating each valve. Fuel flow to the prechambers is controlled by a check valve in the prechamber fuel path that prevents fuel flow into the prechamber when the main chamber pressure is high. The main fuel rail is regulated at the inlet by a fuel control valve that manipulates the gas pressure in the fuel rail. This fuel control valve is driven according to the engine's desired and actual speed signals as they are registered at the engine control module.

A schematic of the G3600 fuel system is shown in **Figure 10**.

To provide a feedback signal for AFRC, the G3600 places a sensor at the outer edge of the main combustion chamber that detects when the flame front of combustion arrives. By measuring the time interval between the firing of the spark plug and the signal from the combustion sensor, each cylinder tells the main engine control about combustion directly in the cylinder. The engine control module combines this information with data on the temperature and pressure of both the fuel and inlet air streams to determine how to tailor the overall engine air/fuel ratio to optimize combustion. Adjustment of air/fuel ratio is accomplished by manipulating the turbo wastegate and inlet air choke to control airflow; more air delivered means a leaner air/fuel ratio.

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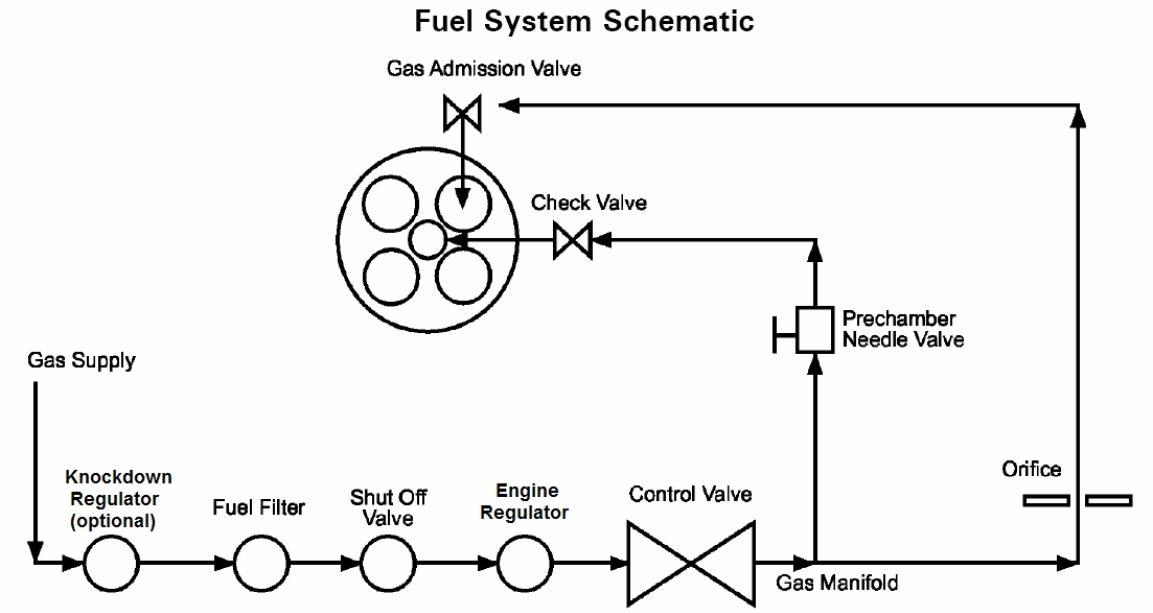

Figure 10

Reference Materials

Media List

The following information is provided as an additional reference to subjects discussed in this manual.

LEBW4977: Gaseous Fuels

LEKQ7260: Low Energy Fuels

LEKQ7742: Detonation and Preignition

LEKQ6378: Caterpillar Methane Number Program

LEKQ9085: G3600 Engine Basics

LEKQ7518: G3500 Engine Basics

LEKQ7511: G3400 Engine Basics

Systems Operation and Troubleshooting sections of the Service Manual

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